GOES SATELLITE TIME CODE DISSEMINATION

R. E. Beehler, Time and Frequency Division, National Bureau of Standards, Boulder, CO 80303

ABSTRACT

The National Bureau of Standards, in cooperation with the National Oceanic and Atmospheric Administration (NOAA), has been disseminating a time code referenced to UTC(NBS) via two of NOAA's geostationary GOES satellites since 1975. A review of the GOES time code system, the performance achieved to date, and some potential improvements in the future will be discussed.

The disseminated time code is originated from a triply redundant set of atomic standards, time code generators and related equipment maintained by NBS at NOAA's Wallops Island, VA satellite control facility. It is relayed by two GOES satellites located at 75°W and 135°W longitude on a continuous basis to users within North and South America (with overlapping coverage) and well out into the Atlantic and Pacific ocean areas. Downlink frequencies are near 468 MHz. The signals from both satellites are monitored and controlled from the NBS labs at Boulder, CO with additional monitoring input from geographically separated receivers in Washington, DC and Hawaii. Received time code accuracies are typically better than 1 ms if the user only applies a constant correction to compensate approximately for his geographical location or better than 100 μs if manual or automatic corrections are applied for path delay using satellite position data encoded into the GOES time code signals.

Performance experience with the received time codes for periods ranging from several years to one day is discussed. Results are also presented for simultaneous, common-view reception by co-located receivers and by receivers separated by several thousand kilometers.

Based on the general acceptance of the GOES time code, NBS and NOAA have recently extended their formal Memorandum-of-Agreement to continue the GOES time code operations for at least an additional five-year period.

INTRODUCTION

In 1975 the National Bureau of Standards (NBS) began regular dissemination of an NBS-referenced time code via two geostationary GOES satellites (Geostationary Operational Environmental Satellites) operated by NOAA (National Oceanic and Atmospheric Administration). The primary mission of the GOES satellites and associated support systems is to gather a variety of environmental data from various sources, including large numbers of remotely located sensing platforms throughout the Western hemisphere, relay the information via the satellites to a central processing facility, and make the processed information available to the World Meteorological Organization and other interested users. The NBS time code is interleaved into the data collection platform interrogation channel, providing a continuously available accurate time-of-day reference both for internal NOAA data handling operations and for more general time and frequency applications throughout much of the Western hemisphere. Commercial time code receivers are readily available for a few thousand dollars that can provide received timing accuracies of better than 100 μs over averaging periods of hours, months, or years.

The cooperative NBS/NOAA program to provide and disseminate the NBS time code via the operational GOES satellites was formalized for a five-year period in May, 1977 by an NBS/NOAA Memorandum-of-Agreement, which was extended by both organizations in May, 1982 for an additional five-year period. Since 1975, significant improvements have been made in the NBS time code generation and control equipment at the GOES Satellite Control Facility at Wallops Island, VA; the time code control and monitoring procedures used by NBS to assure overall system accuracy and reliability; and in the newer generations of the GOES satellites themselves. In the remainder of this paper the overall GOES time code system will be described, including some recent improvements. Performance of the system during the past four years will be discussed based on reception of the time code at NBS/Boulder, the U.S. Naval Observatory in Washington, DC, and at NBS radio station WWVH in Hawaii. Finally, some potential future improvements will be described briefly.

GOES SYSTEM DESCRIPTION

The GOES time code system consists of an NBS-owned time code generation, monitoring, and control system at NOAA's Wallops Island site; the satellite uplink facilities at Wallops Island; the East and West operational GOES satellites located at 75°W and 135°W longitude, respectively; monitoring, computing, and data storage facilities at NBS/Boulder; a two-way dial-up data communication link between Boulder and Wallops Island; and support operations such as NOAA's satellite tracking operations. The triply-redundant time-code-generation system is based on three atomic standards, presently consisting of two cesium standards and one rubidium device. The time code used is specially designed for compatibility with the GOES Data Collection System and has been described in previous publications.[1] The code as transmitted via the two GOES satellites includes complete time-of-year information; DUT1 values -- i.e., estimates of the current difference between the UT1 and UTC time scales; and satellite position information for computing path delays. The

NBS equipment at Wallops Island also includes capabilities for measuring and storing various time difference data, fault detection and alarm circuitry, provisions for monitoring Loran-C transmissions as an independent timing reference, memory for storing 10 days worth of position prediction data for each of the two operational satellites, and modems for use with the Boulder-Wallops Island data link.

The time code is continuously transmitted from this system to the east and west GOES satellites at S-band and is then downlinked on two slightly different frequencies near 468 MHz in one of the meteorological satellite allocated bands. This constraint to use meteorological satellite frequency allocations for the GOES/East and GOES/West downlinks may result in interference in receiving the time code transmissions in some urban areas, since these allocations are shared with the very large and very active land-mobile service. Furthermore, the land-mobile use is designated as the "primary" one within the U.S. while the meteorological satellite use is "secondary." In practical terms this means that if interference to the time code is experienced from land-mobile transmissions, it must be tolerated. Fortunately, time code receivers can be designed to effectively ignore much of this type of interference when necessary. In general, the time code as received from GOES/East is less affected by interference than that from GOES/West because one of the land-mobile channels exactly coincides with the GOES/West frequency while the closest one to the GOES/ East frequency is somewhat offset.

The satellite position information included in the time code format is generated from a sophisticated, very large orbit prediction program run on a large computer at NBS/Boulder. Data inputs for this program include the satellite orbital elements which are determined from satellite tracking data obtained by NOAA and/or NASA. The computer program generates position predictions for each satellite for each hour during the next ten-day period and these are further processed by the microprocessor-based time code generation equipment at Wallops Island to generate updated values each four minutes that are then encoded along with the time information. Users then have the option to simply decode the received time information achieving accuracies of about 1 ms or to also use the position data to compute a path delay from Wallops Island to the user's particular location that is updated each four minutes to compensate for movements of the satellites. In the latter case, timing accuracies of better than 100 μs can be achieved. GOES timing accuracy as transmitted from Wallops Island is maintained to within at least 10 μs by continuous monitoring relative to Loran-C and by occasional portable clock trips.

Reception of the GOES time code is possible on a continuous basis throughout much of the Western hemisphere as shown by the coverage maps for both satellites in Figure 1. Overlapping coverage is provided within the continental U.S. and certain other areas. While there are also operational satellites in the European (METEOSAT) and Japanese (GMS) regions that are part of the same worldwide meteorological satellite system as GOES, these satellites do not currently include an identical or similar time code in their broadcast formats. Several forms of commercial GOES time code receivers are currently available which feature automatic operation with small antennas. Prices range from about \$2800 to \$4000, depending on the accuracy level provided.

As the GOES time code system and operational procedures have evolved during the past few years, several improvements have been incorporated. A second-generation system has been installed at Wallops Island that provides increased reliability through triple redundancy, more elaborate diagnostic information available remotely to NBS/Boulder personnel, and the replacement of two rubidium standards with more stable (in long term) cesium devices. The information transmitted to users has been expanded to include higher-resolution satellite position data and UT1 time scale information. Monitoring has also been expanded by placing receivers at the U.S. Naval Observatory in Washington, DC and at radio station WWVH in Hawaii to provide better geographical coverage and by acquiring dedicated backup receivers for the NBS/Boulder system. GOES status information is now available to interested users via the monthly NBS Time and Frequency Bulletin[(2)] and, on a more current basis, from the USNO Automated Data Service. The USNO system can be accessed using a variety of terminals at either 300 or 1200 baud with even parity. Telephone access numbers are: (202) 653-1079 (commercial); 653-1079 (FTS); and 294-1079 (Autovon). After responding to the prompt asking for identification, the GOES status information is obtained by requesting the file "NBSGO" with the command "@ NBSGO" followed by a carriage return. These status reports are designed to report interruptions in service, temporary perturbations in operations which result in reduced reception accuracies or other problems, and accomplished or projected changes that affect the GOES time code. Possible additional future improvements are discussed at the end of this paper.

OBSERVED TIME CODE PERFORMANCE

In general there are three different modes in which the GOES time code can be used:

1) Uncorrected. In this mode the received time signal is simply decoded and used without using the position information in the signal to compute and compensate for path delays as they change due to satellite motion. The transmitted time code is advanced by a fixed 260,000 μs. The received signals nevertheless arrive at any point within the coverage area within ±16 ms of UTC(NBS). Furthermore, a fixed-location user can compensate for most of this fixed bias by applying a fixed correction which depends on his specific location to all received data. If this procedure is followed, the received time signal will provide an accurate local UTC reference that varies less than 1 ms in long term due to uncompensated satellite motion. In the discussions of time code performance that follow, the term "uncorrected" will refer to this mode of reception;

2) Corrected. In this mode either the user or the automatic receiver uses the satellite position data in the received timing signal and the known geographical locations of his site and the Wallops Island origination point to compute a specific path delay that can be updated each four minutes as the satellite position varies. When these corrections are applied to the received time code, either manually or automatically, a local version of UTC(NBS) is provided, generally accurate to within ±100 μs. This received accuracy at the user's site is deteriorated relative to the "as-transmitted" accuracy of about 10 μs because the satellite position predictions used to compute path delays contain some uncertainties. Also, uncertainties and instabilities in the receiver delays can contribute to the usable accuracy as received. In the following discussions of received data this mode will be referred to as "corrected"; and

3) Common-view. In this mode multiple users at separated sites within the coverage area of the same satellite can compare their local clocks with one another by making simultaneous measurements of the received time code at each site. Simple subtraction of the results between two sites yields clock differences that to some degree are insensitive to the actual satellite position and any time errors that may exist between UTC and the transmitted code. In this case the received timing signal functions only as a "transfer standard" to compare two or more clocks.

Observed Performance in "Uncorrected" Mode

Figures 2-5 show some of the results of monitoring the uncorrected GOES/East and GOES/West time codes at NBS/Boulder. In all cases the Y-axis is (UTC(NBS) - the received time code) in microseconds with no correction being applied for Boulder's fixed location. Figures 2 and 3 show typical results (for GOES/East and GOES/West, respectively) over a period of several weeks where each plotted point is an hourly measurement of (UTC(NBS) - received signal). The obvious variations within each day are due to satellite motion which varies the path delay. For GOES/East during this period the maximum peak-to-peak variation was less than 200 μs. The GOES/West hourly data in Figure 3 show somewhat larger daily variations of about 250 μs during part of the period and a definite change on day #19 when a GOES/West satellite station-keeping maneuver was executed. Figures 3 and 4 show the longer term variations in the received "uncorrected" time codes over a period of nearly four years. In these plots the points up to 5/1/81 (day number 852) are actually single measurements made once each day, while after 5/1/81 an average of 24 hourly measurements is plotted for each day. The somewhat-more-erratic values prior to 5/1/81 are due mainly to the greater sensitivity of single measurements to temporary perturbations from such causes as land-mobile interference. The many points where abrupt changes occur, producing the "scalloped" appearance, correspond to days on which satellite station-keeping maneuvers took place. Note especially in Figure 4 how the station-keeping on GOES/East has improved since the shift to a new GOES/East satellite (GOES-5) at about day #970 on the plot. The important point, however, is that during the entire four-year period both satellites provided a UTC time reference that varied by less than ±1 ms with respect to a fixed offset due to Boulder's geographical location.

Observed Performance in "Corrected" Mode

Figures 6-9 show received data obtained with commercial receivers that automatically use the satellite position data to compute updated path delays and adjust the output 1pps pulse accordingly. In each plot the Y-axis runs from -200 μs to +200 μs with respect to UTC(NBS). Figure 6 shows the relatively short-term performance for both satellites by plotting hourly measurements over a typical 1-month period. The peak-to-peak variations within each day, ranging from about 10 to 35 μs during this period, are apparently due to small imperfections in the tracking data, orbital-element generation, or the computer program used to generate the satellite position predictions. Abrupt changes in the peak-to-peak amplitude of the daily variations are sometimes observed when a new set of orbital elements is processed (about once per week). Also, a general increase in the amplitude sometimes occurs as the time increases since the last "fresh" set of orbital elements -- e.g., note the first eight days of GOES/West data in Figure 6. Based on years of monitoring at NBS the typical peak-to-peak daily variation is about 20 μs, although there have been occasional periods due to lower-quality orbital elements when values of greater than 100 μs were observed.

Figure 7 shows corresponding data over a longer period of 4½ months where an average of 24 hourly measurements is plotted each day. The step change of about 40 μs that occurred in GOES/West early in August, 1982 has no apparent explanation. The more temporary large excursions of up to 150 μs in GOES/West that occurred during a two-week period around day #90 resulted from two consecutive sets of orbital elements that were of poor quality.

Figures 8 and 9 show the long-term performance over nearly four years of the GOES/East and GOES/West time codes, respectively, as received at NBS/Boulder. Each point prior to May 1, 1981 (day number 852) is a single measurement per day while each point after that time is a daily average of hourly measurements. Considering the entire period of more than 1400 days, the received time codes from both satellites, averaged over a day, have generally remained within ±100 μs of UTC(NBS) with the exception of occasional brief periods of 1-15 days.

Based on the experience at NBS during 1982 (325 days), a GOES/East time code user would have observed daily averages within ±25 μs of the mean value 95% of the time and no values greater than 50 μs from the mean. A corresponding GOES/West user, however, would have observed only about 65% of the values falling within ±25 μs of the mean, although 93% of them would be within ±50 μs.

Observed Performance in "Common-view" Mode

Figures 10-12 summarize the relatively short-term performance over about a 1-month period when the GOES time code is used in the "common-view" mode. In Figure 10, the hourly measurements of GOES/East are plotted from two co-located receivers at NBS/Boulder along with the hourly differences in the values. Although the output of each receiver has time code variations of several tens of microseconds, the differences between the simultaneous hourly measurements remain generally stable to within a few microseconds with occasional jumps of 5-10 μs.

Figures 11 and 12 show similar data for receivers which are separated thousands of kilometers. Figure 11 applies to the simultaneous reception of GOES/East at NBS/Boulder and the USNO in Washington, DC while Figure 12 applies to reception of GOES/West in Boulder and Hawaii. Although the Boulder/Washington differences are not much worse than for the co-located receivers, the Boulder/Hawaii differences show larger variations and a relatively large step change at about day #25 on the plot. The Boulder/Hawaii data may be adversely affected by the greater sensitivity of the GOES/West downlink frequency to land-mobile interference and by the fact that the Hawaii receiver is an older model, not containing some improvements incorporated into the later versions used in Boulder and Washington.

Figure 13 presents all of the NBS/USNO common-view data currently available, but in this case, using daily averages of the hourly measurements at each site. At present it is not clear why the results seemed to improve since early October, 1982. Finally, all the available Boulder/Hawaii common-view differences based on daily averages are shown in Figure 14. The data gap in mid 1982 results from a failure in the receiver at WWVH. The observed common-view performance with GOES/West during this period is clearly inferior to the NBS/USNO comparisons via GOES/East. Further testing will be necessary in order to identify the specific cause or causes.

Based on the available data to date it appears that the common-view approach with GOES should not be depended on for comparisons of separated clocks to better than 10 μs. Such a result is probably not too surprising in view of the constraints imposed by the 400-Hertz bandwidth limitation on the GOES time code channel.

SOME POTENTIAL FUTURE IMPROVEMENTS

1) NBS Access to More Current Position Data. Under present operating procedures, there sometimes are substantial delays between the creation of a revised set of satellite orbital elements by NOAA or NASA and the time at which new position predictions based on them can be inserted into the time code transmissions. The current procedure requires distribution of the orbital elements from NOAA to NASA and then to NBS, the running of a large computer program in Boulder to generate the revised position data, and the transmittal of

these predictions to the Wallops Island equipment. The delays involved may be particularly significant at times when satellite maneuvers are implemented. Efforts are now in progress to streamline this process by developing direct access by NBS to the most current satellite data residing in NOAA's computer at Suitland, MD. It may also prove feasible to generate improved position predictions more quickly and more efficiently directly from the GOES tracking data obtained approximately every four hours for each satellite.

2) Accuracy Indicators in Time Code. Suggestions to include in the time code format some indicator of when the usable accuracy is degraded due to various reasons are under consideration. Unused code bits are available for this purpose and receiver manufacturers have indicated willingness to provide a corresponding visible or other form of alert at the user's receiver as appropriate.

3) Automatic Compensation for Eclipse Periods. Due to GOES spacecraft limitations the time code transmissions are shifted to an in-orbit spare satellite at 106°W longitude for scheduled 2-hour periods each day during eclipse periods (March 1-April 15 and Sept. 1-Oct 15). During these 2-hour periods the satellite position data cannot at present be revised to reflect the spare satellite's position. Changes to the GOES time code system software at Wallops Island are being considered to alleviate this problem.

4) Automatic Delay Monitoring at Wallops Island. At present equipment delays through the Wallops Island transmission channel processing equipment are not monitored directly and could introduce uncompensated changes in path delay when subsystems are replaced or modified. Capabilities for monitoring such station delays may be incorporated in the future.

5) Use of GOES Trilateration System for Higher Accuracy Time Transfer. Some of the current limitations in GOES timing accuracy are related to the limited 400-Hz interrogation-channel bandwidth available and uncertainties in the satellite position predictions. NBS plans to investigate the possibility of removing or reducing these limitations through the use of the GOES trilateration ranging system for time transfer. Ranging signals are transmitted at about 1.6 GHz approximately every four hours. With sidetones as high as 200 kHz, these ranging signals could provide timing resolution in the 1 ns range. Furthermore, since the satellite positions are determined accurately during each of the ranging operations, time transfers should be possible at these times with both higher precision and higher accuracy. Benefits may be realizable in both a general dissemination mode and a higher accuracy common-view comparison mode.

ACKNOWLEDGEMENT

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the U. S. Naval Observatory in making possible the additional GOES/East monitoring capability in Washington, DC and also USNO's provision of its Automated Data Service facilities for the GOES status reports.

REFERENCES

(1) D.W. Hanson, D.D. Davis, and J.V. Cateora. NBS time to the western hemisphere by satellite. Radio Science, vol. 14, No. 4, p. 731-740 (July-August 1979).

(2) NBS Time and Frequency Bulletin. Available upon request to Time and Frequency Division, National Bureau of Standards, 325 Broadway, Boulder, CO 80303.

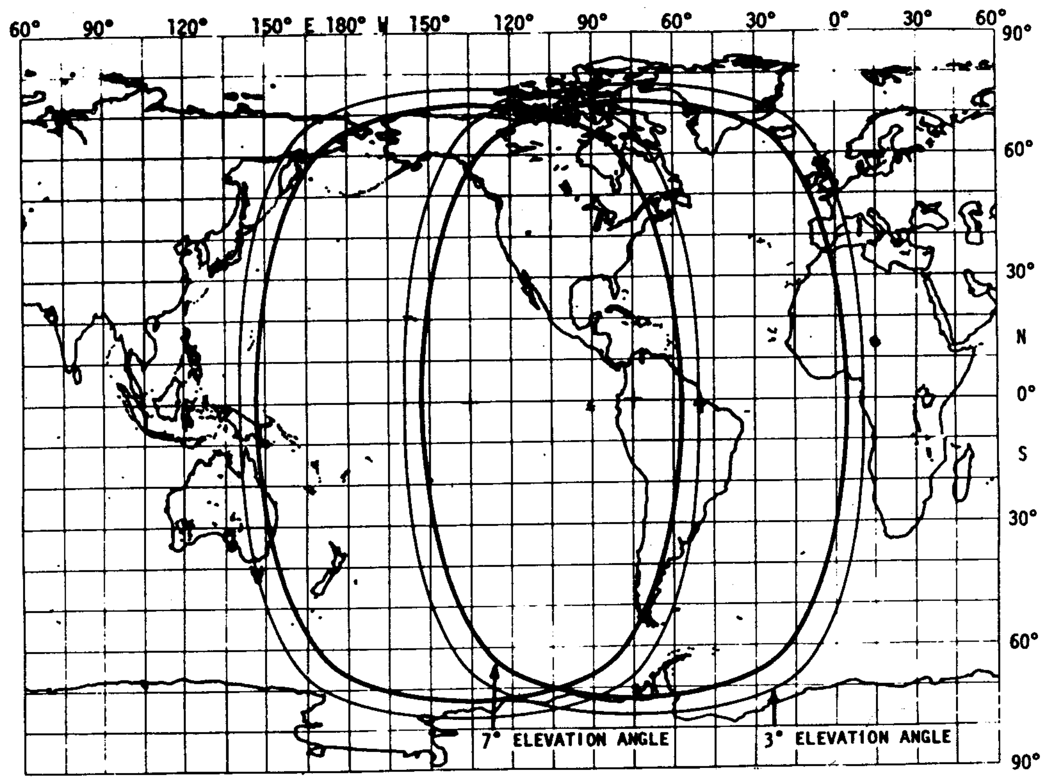
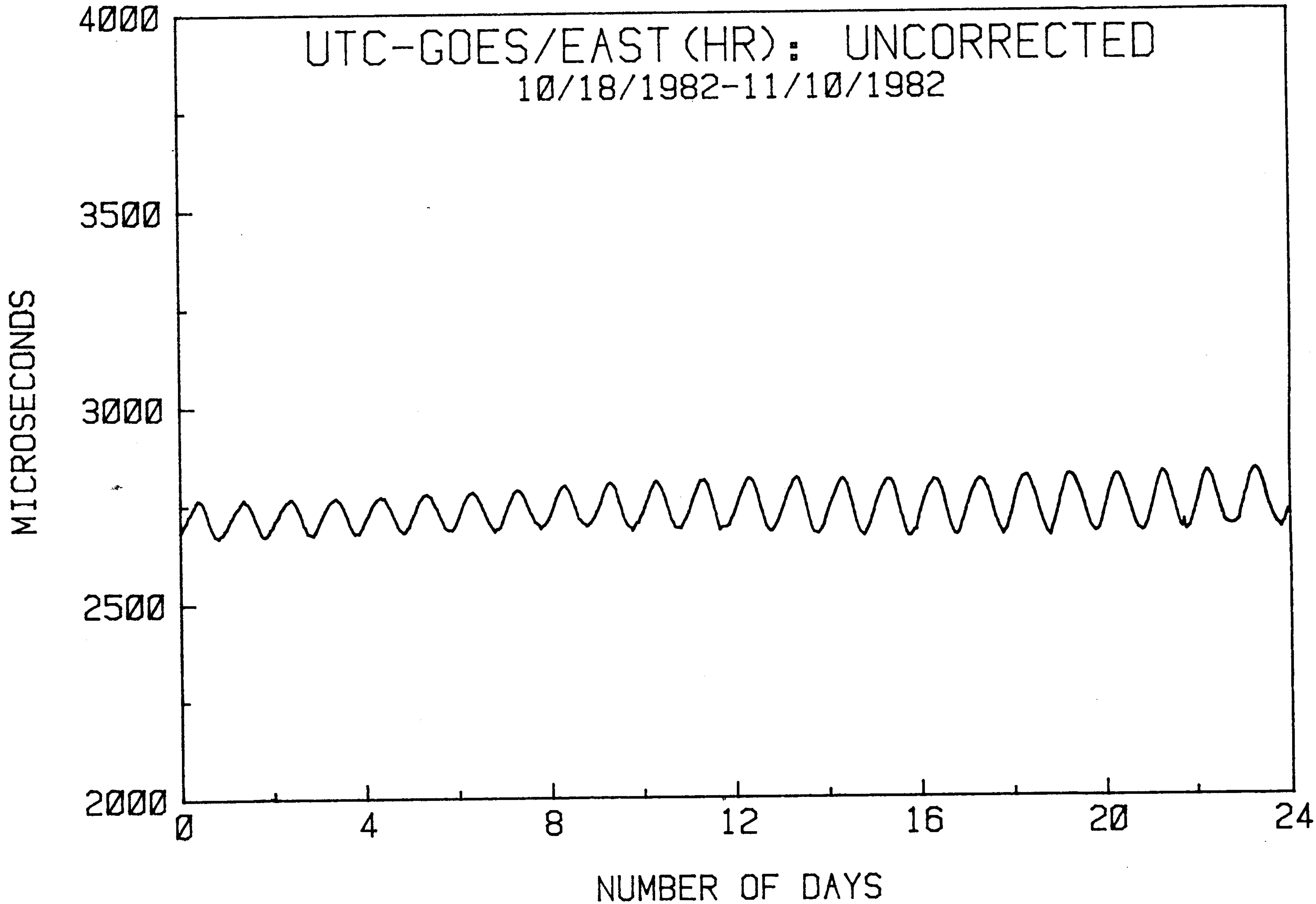
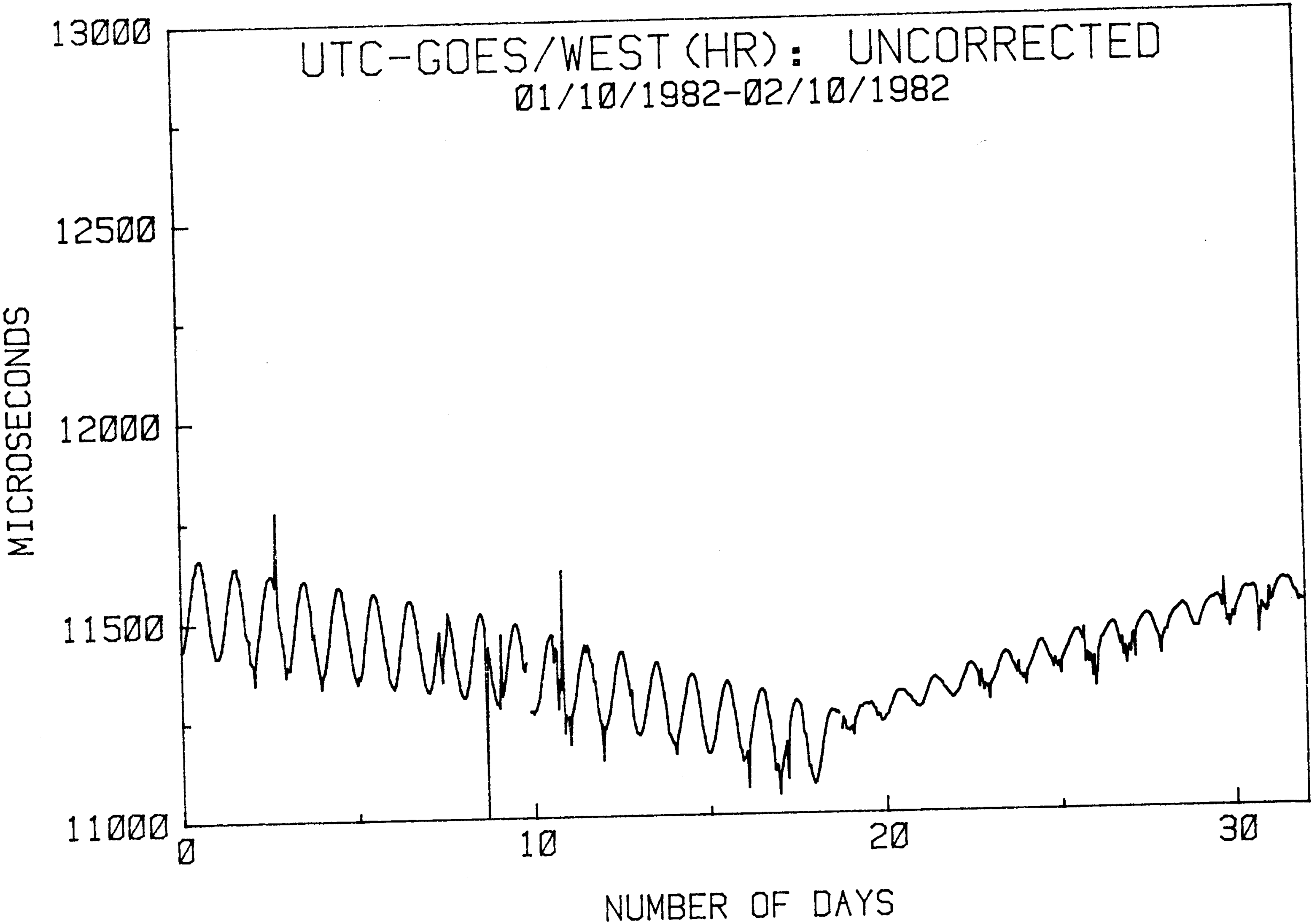


Figure 1. GOES/East and GOES/West coverage areas.



UTC-GOES/EAST (HR): UNCORRECTED
10/18/1982-11/10/1982
4000
3500
3000
2500
2000
MICROSECONDS
0
4
8
12
16
20
24
NUMBER OF DAYS

Figure 2



UTC-GOES/WEST (HR): UNCORRECTED
01/10/1982-02/10/1982
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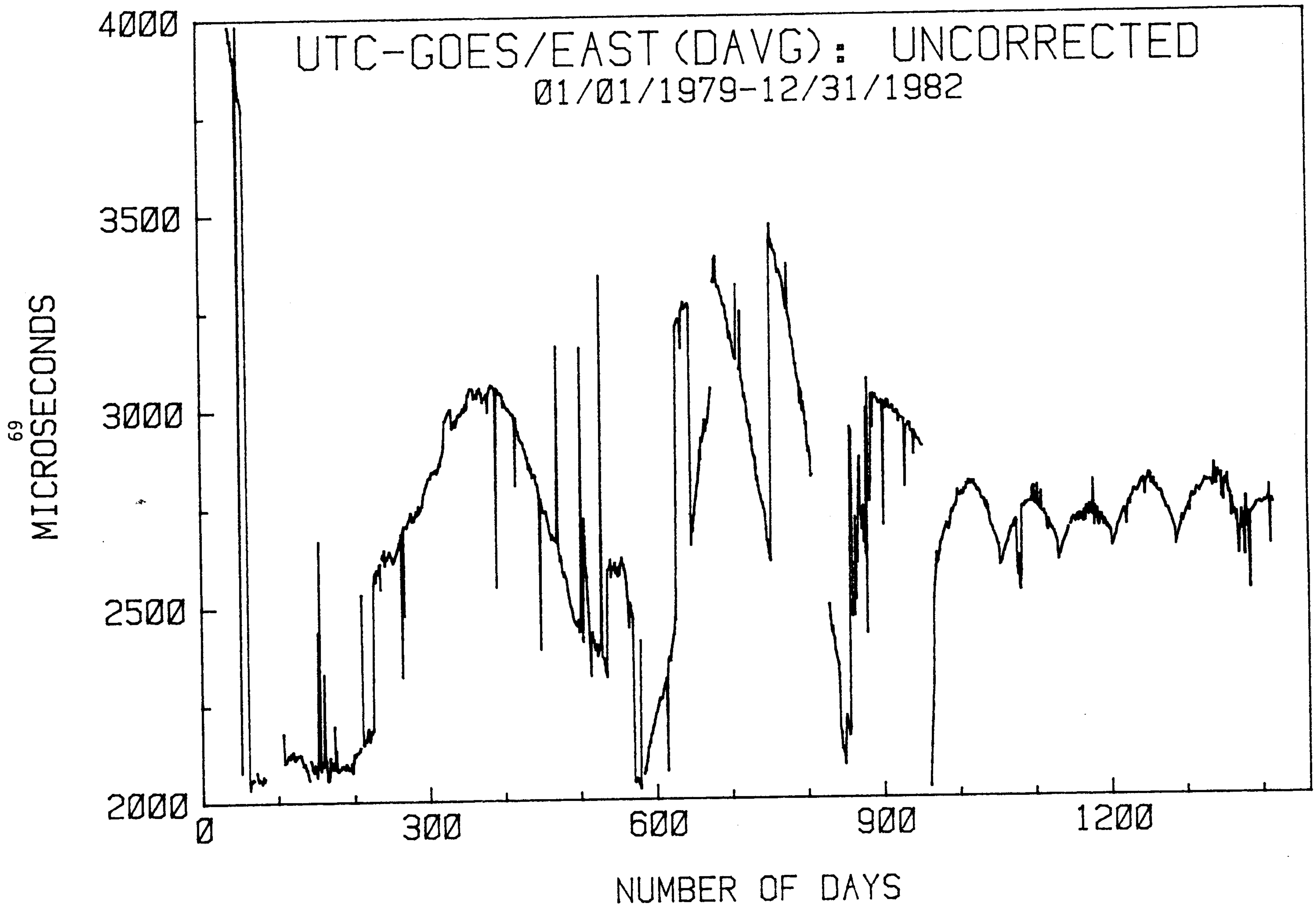
12500
12000
11500
11000
MICROSECONDS
0
10
20
30
NUMBER OF DAYS

Figure 3



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3500
3000
2500
2000
MICROSECONDS
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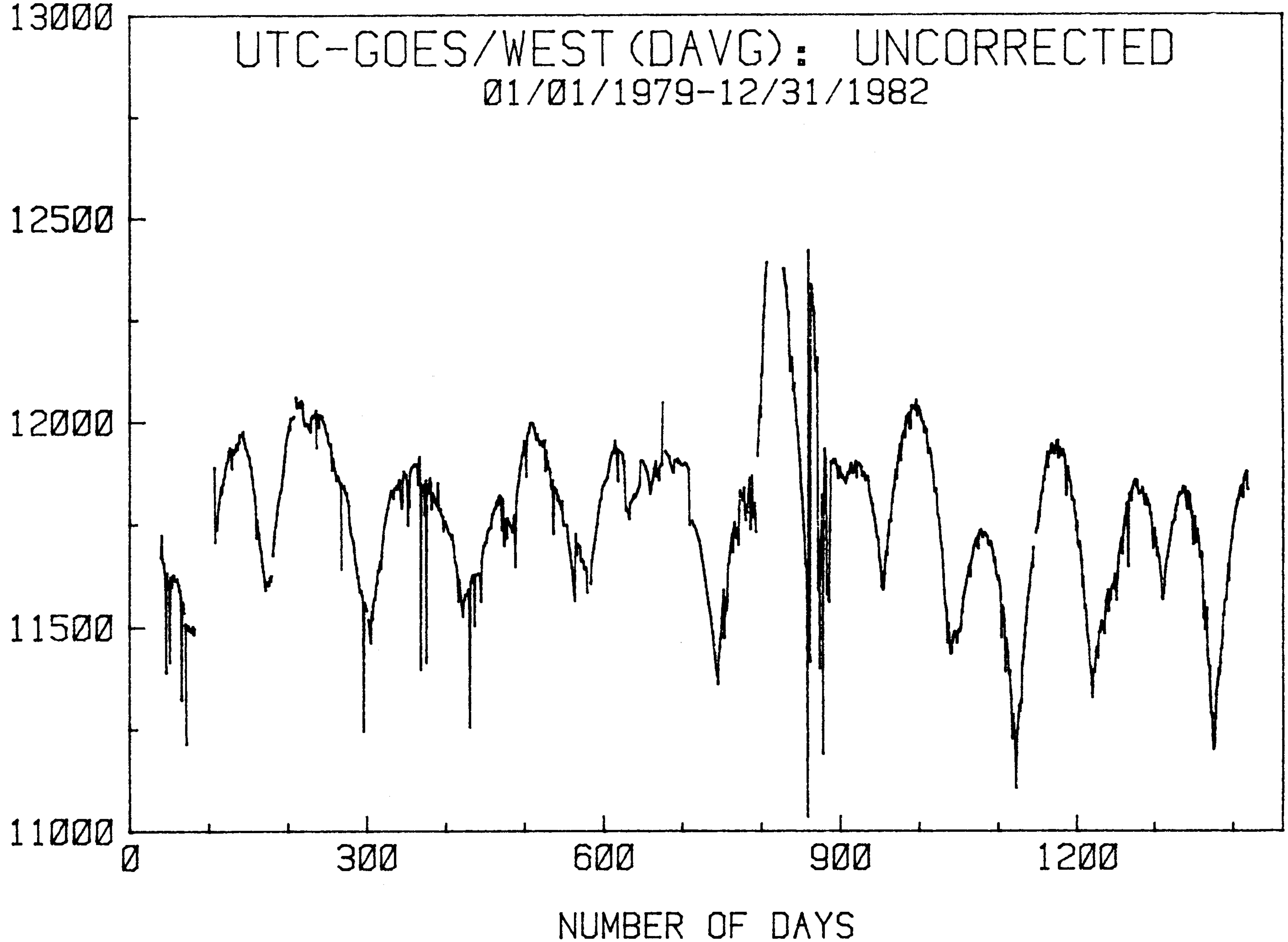
300
600
900
1200
NUMBER OF DAYS

Figure 4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01/01/1979-12/31/1982
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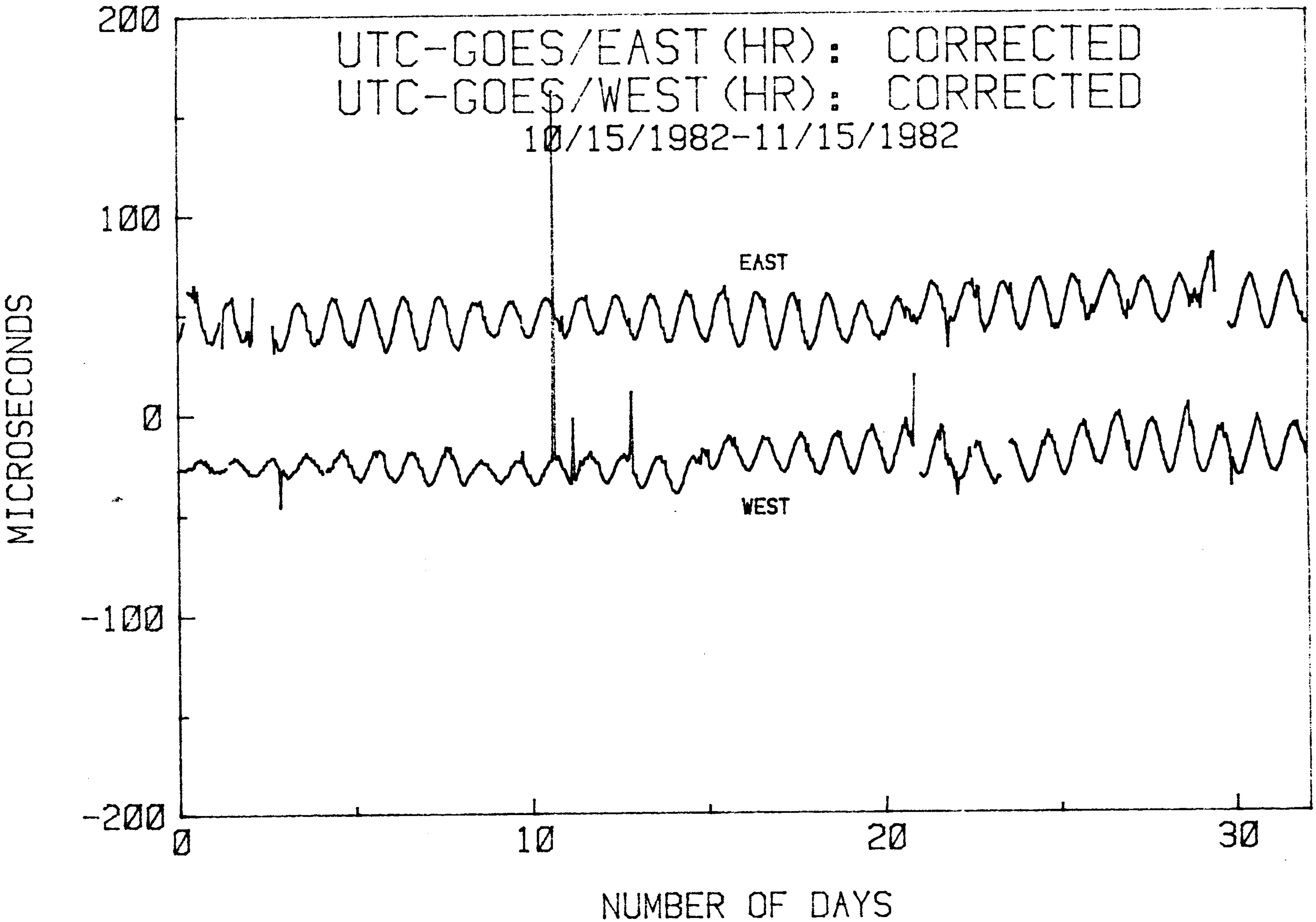
12500
12000
11500
11000
MICROSECONDS
0
300
600
900
1200
NUMBER OF DAYS

Figure 5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UTC-GOES/WEST(HR): CORRECTED
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WEST
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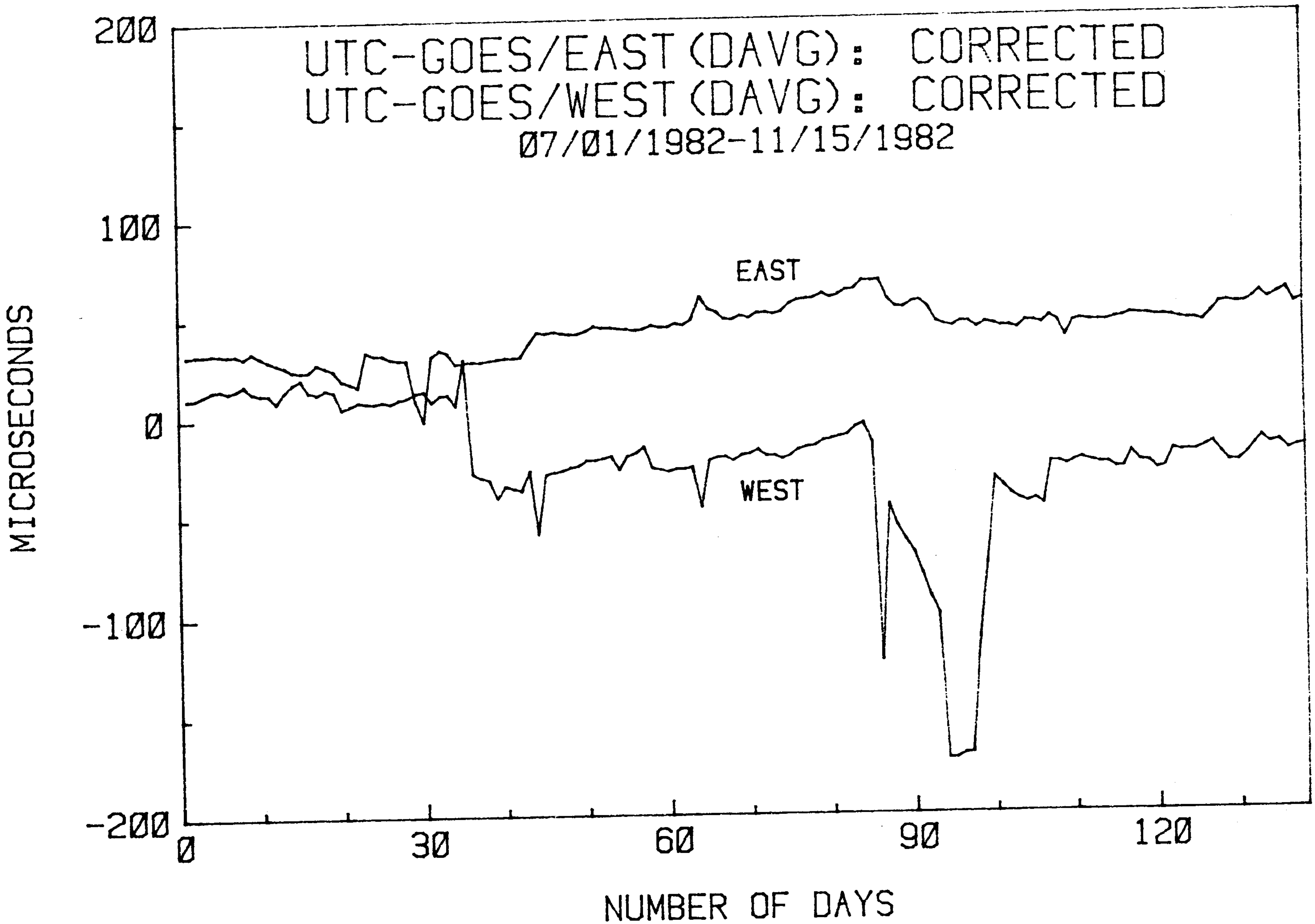
-100
-200
MICROSECONDS
0
10
20
30
NUMBER OF DAYS

Figure 6



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UTC-GOES/WEST(DAVG): CORRECTED
07/01/1982-11/15/1982
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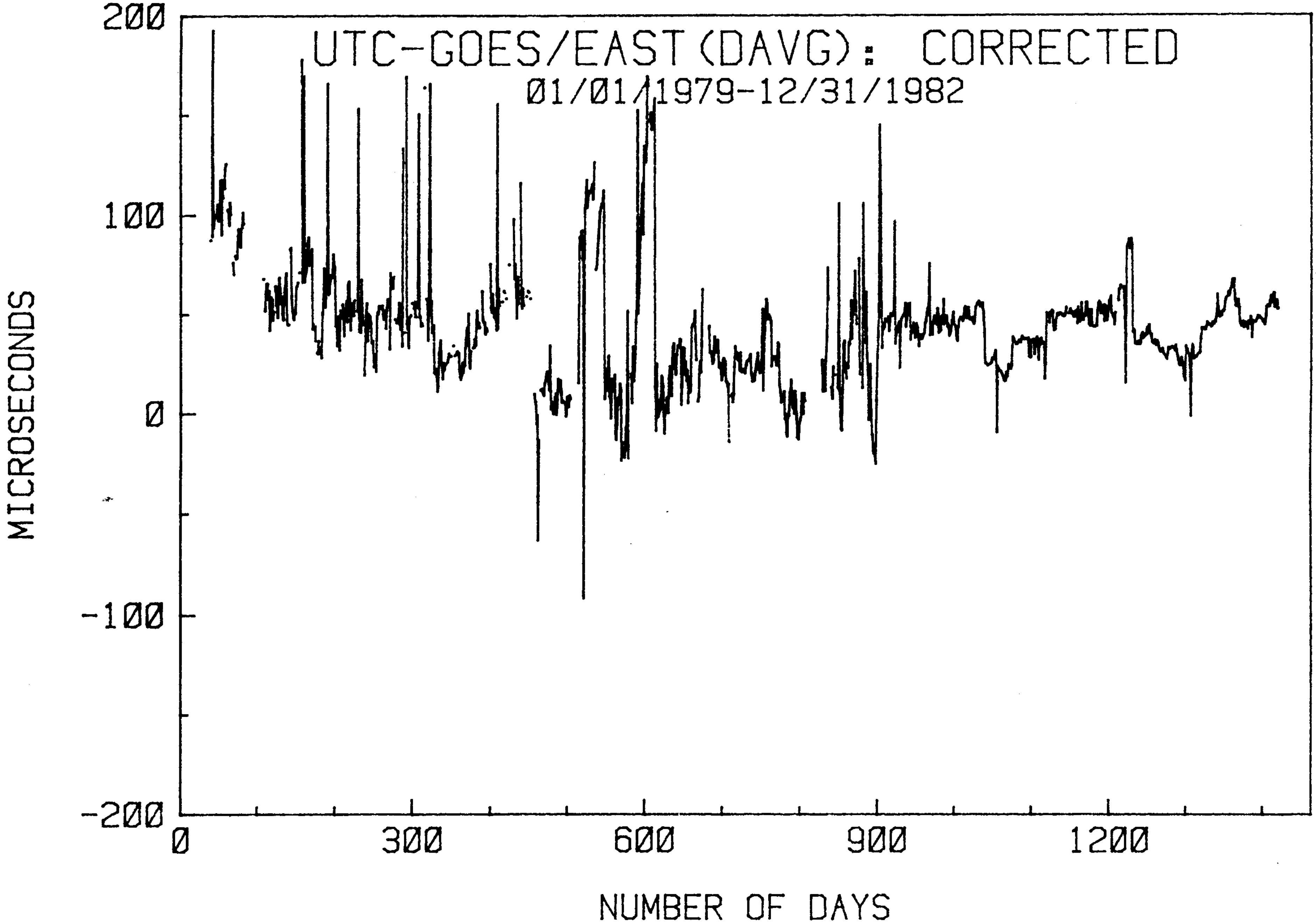
WEST
200
100
0
-100
-200
MICROSECONDS
0
30
60
90
120
NUMBER OF DAYS

Figure 7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Ø1/Ø1/1979-12/31/1982
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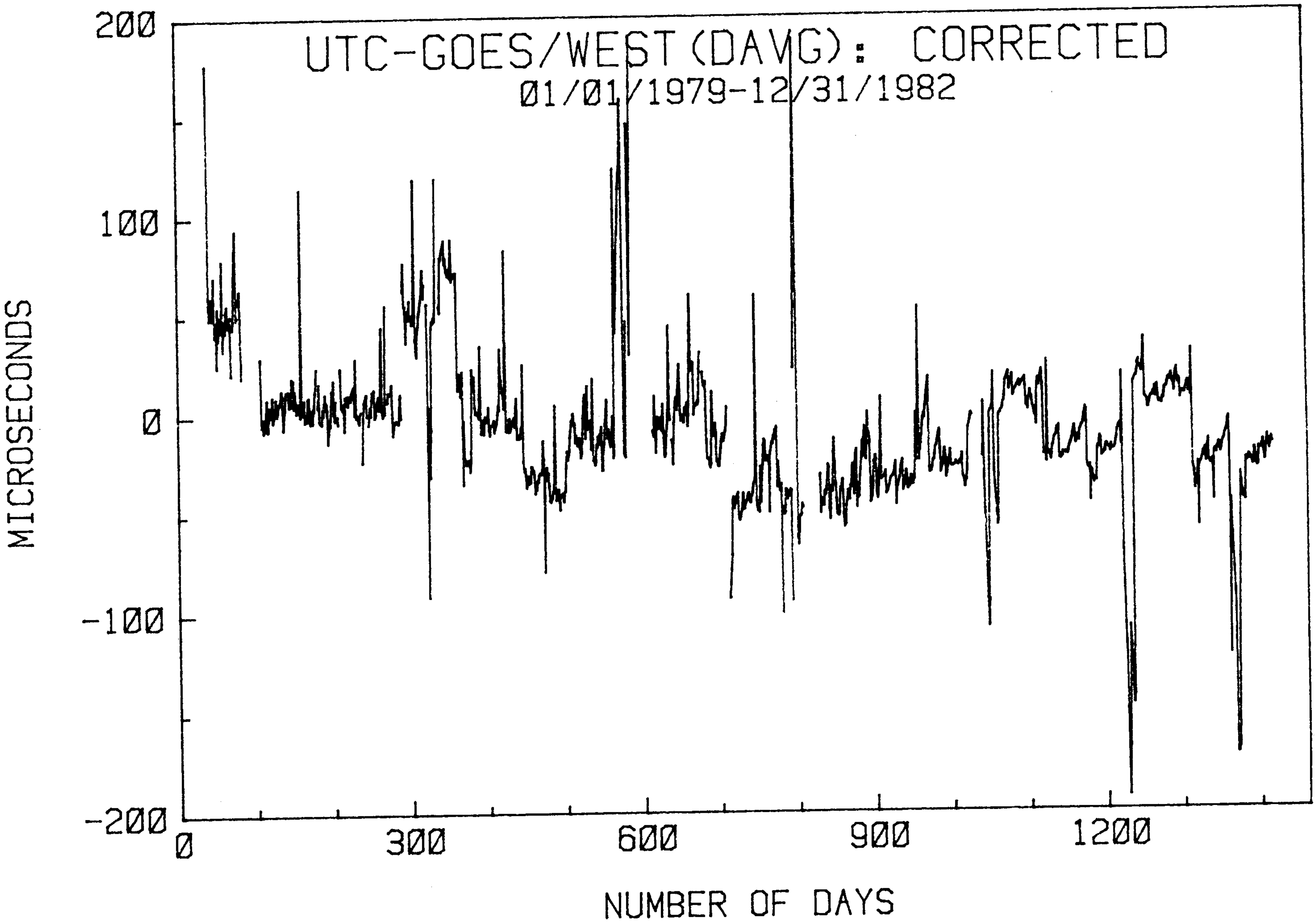
Ø
-100
-200
MICROSECONDS
Ø
300
600
900
1200
NUMBER OF DAYS

Figure 8



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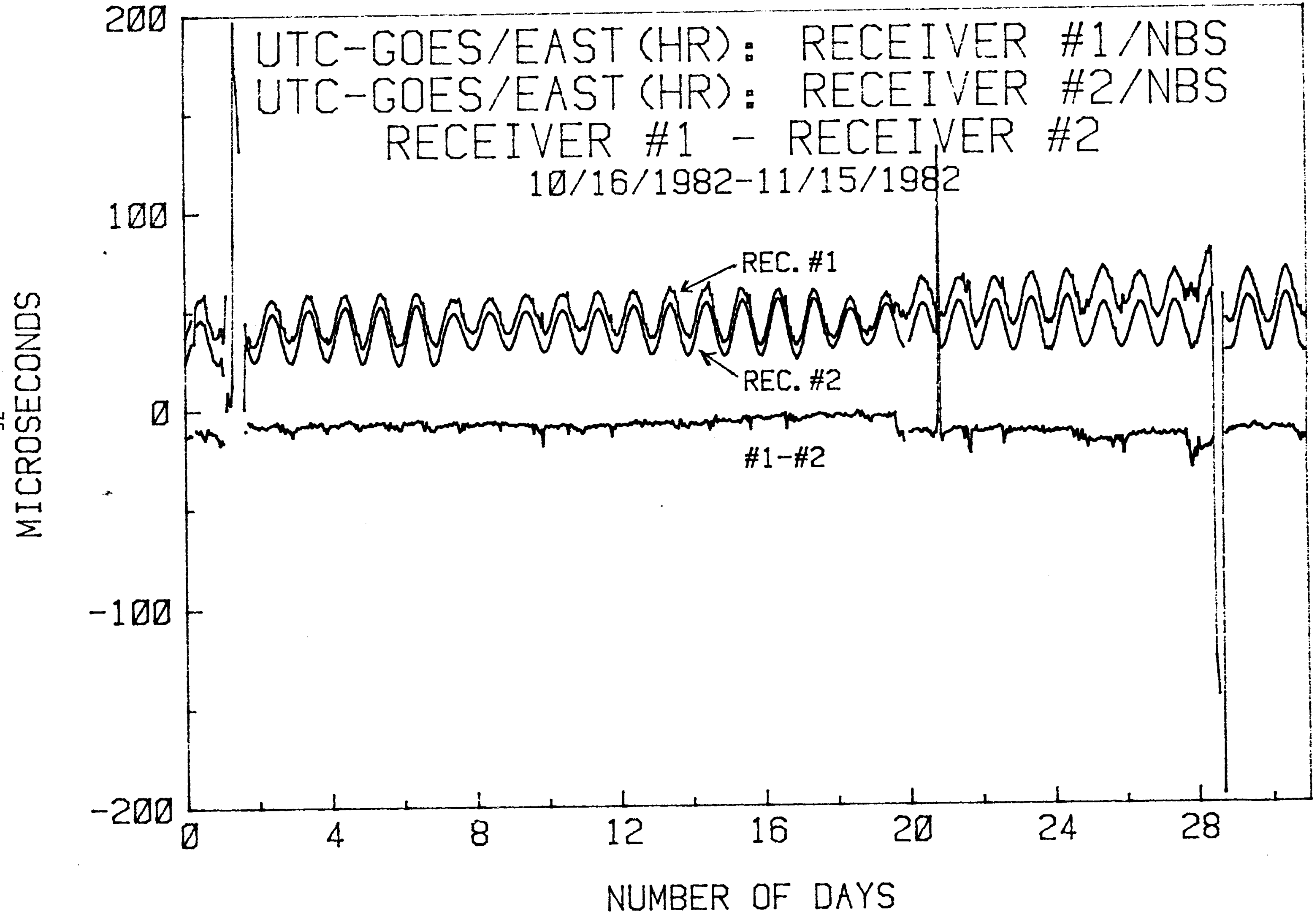
Ø1/Ø1/1979-12/31/1982
200
100
Ø
-100
-200
MICROSECONDS
Ø
300
600
900
1200
NUMBER OF DAYS

Figure 9



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UTC-GOES/EAST(HR): RECEIVER #2/NBS
RECEIVER #1 - RECEIVER #2
10/16/1982-11/15/1982
REC. #1
REC. #2
#1-#2
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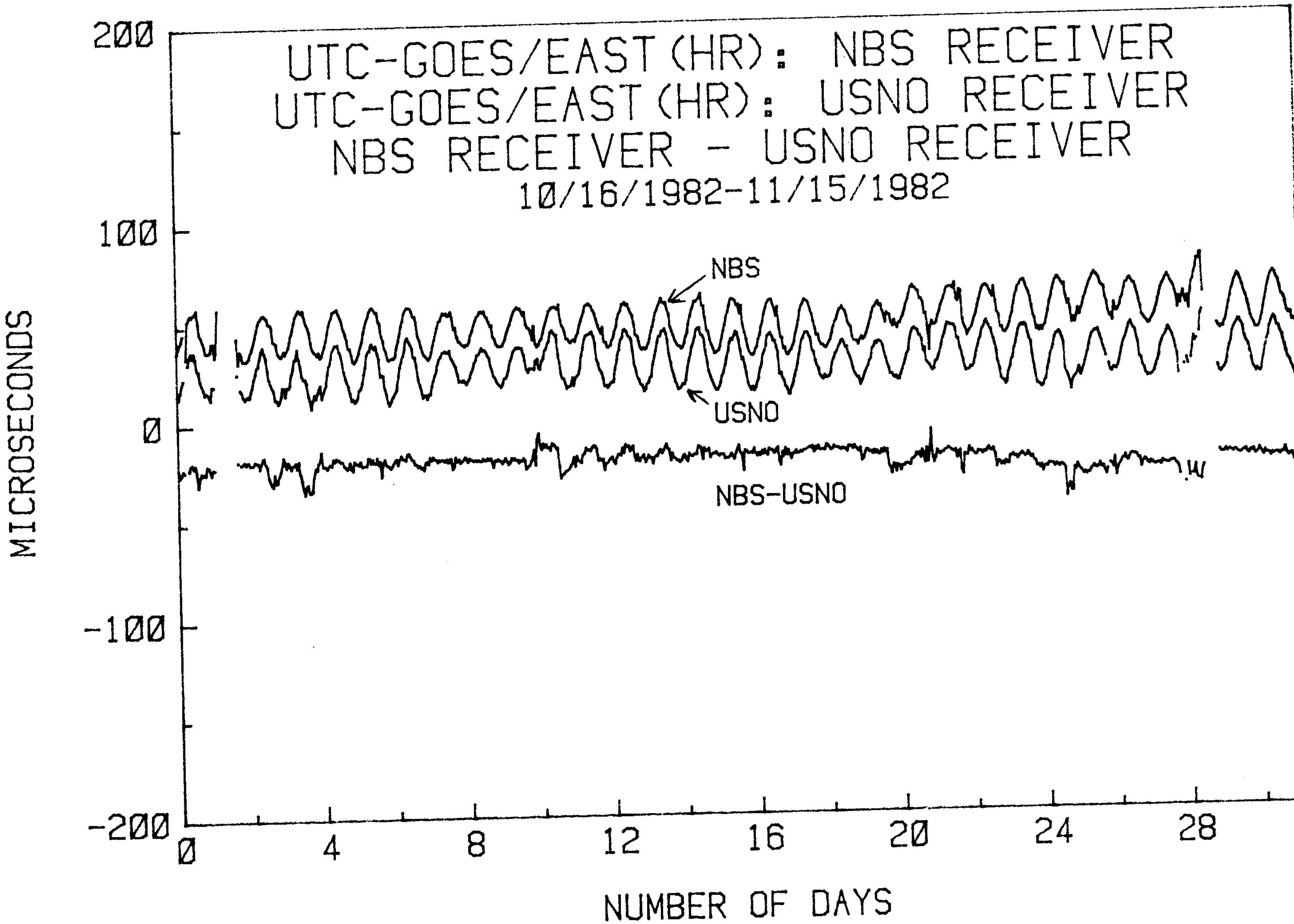
100
0
-100
-200
MICROSECONDS
0
4
8
12
16
20
24
28
NUMBER OF DAYS

Figure 10


UTC-GOES/EAST(HR): NBS RECEIVER
UTC-GOES/EAST(HR): USNO RECEIVER
NBS RECEIVER - USNO RECEIVER
10/16/1982-11/15/1982
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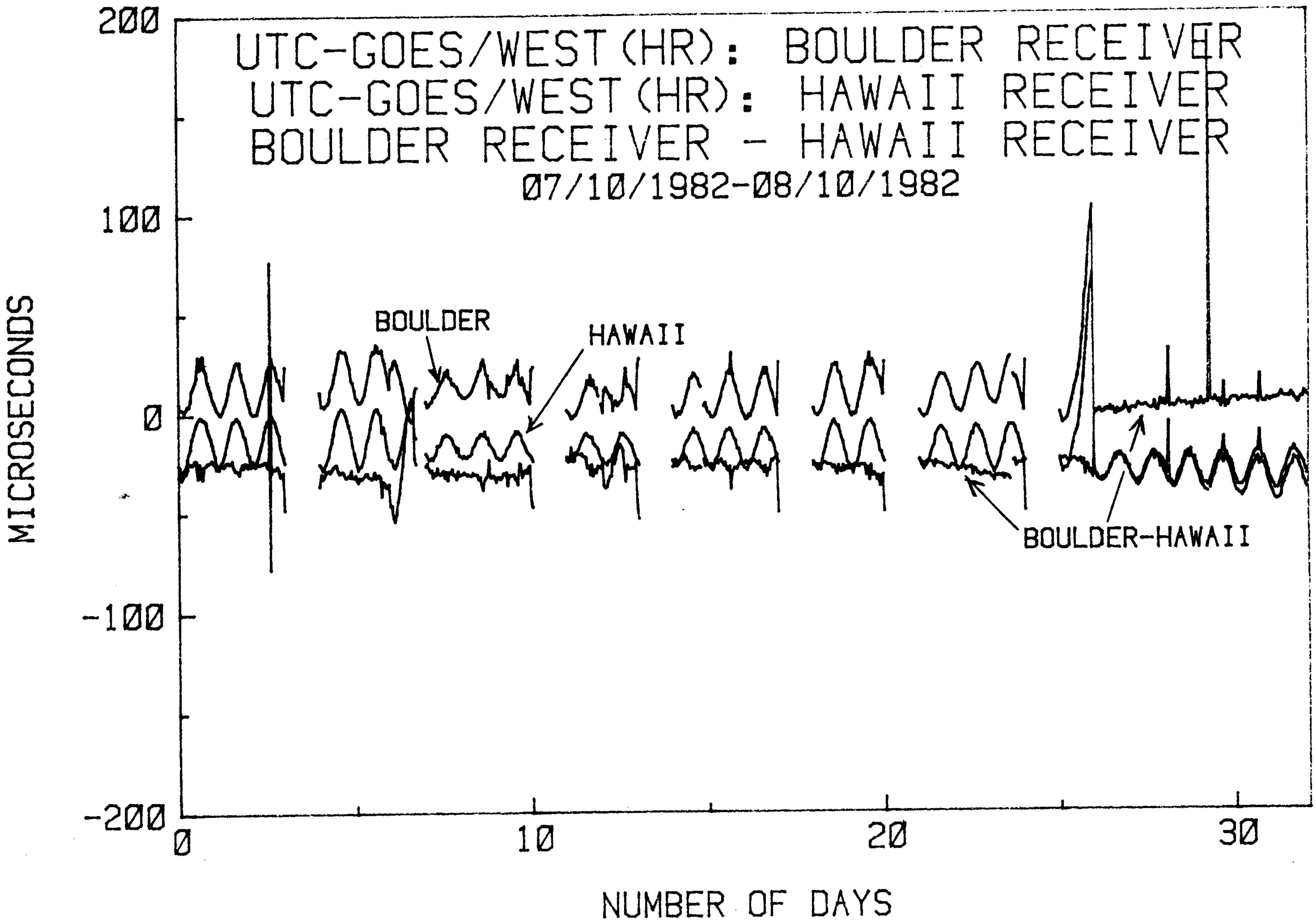
USNO
NBS-USNO
MICROSECONDS
200
100
0
-100
-200
0
4
8
12
16
20
24
28
NUMBER OF DAYS
Figure 11


UTC-GOES/WEST(HR): BOULDER RECEIVER
UTC-GOES/WEST(HR): HAWAII RECEIVER
BOULDER RECEIVER - HAWAII RECEIVER
07/10/1982-08/10/1982
BOULDER
HAWAII
BOULDER-HAWAII
MICROSECONDS
200
100
0
-100
-200
0
10
20
30
NUMBER OF DAYS
Figure 12

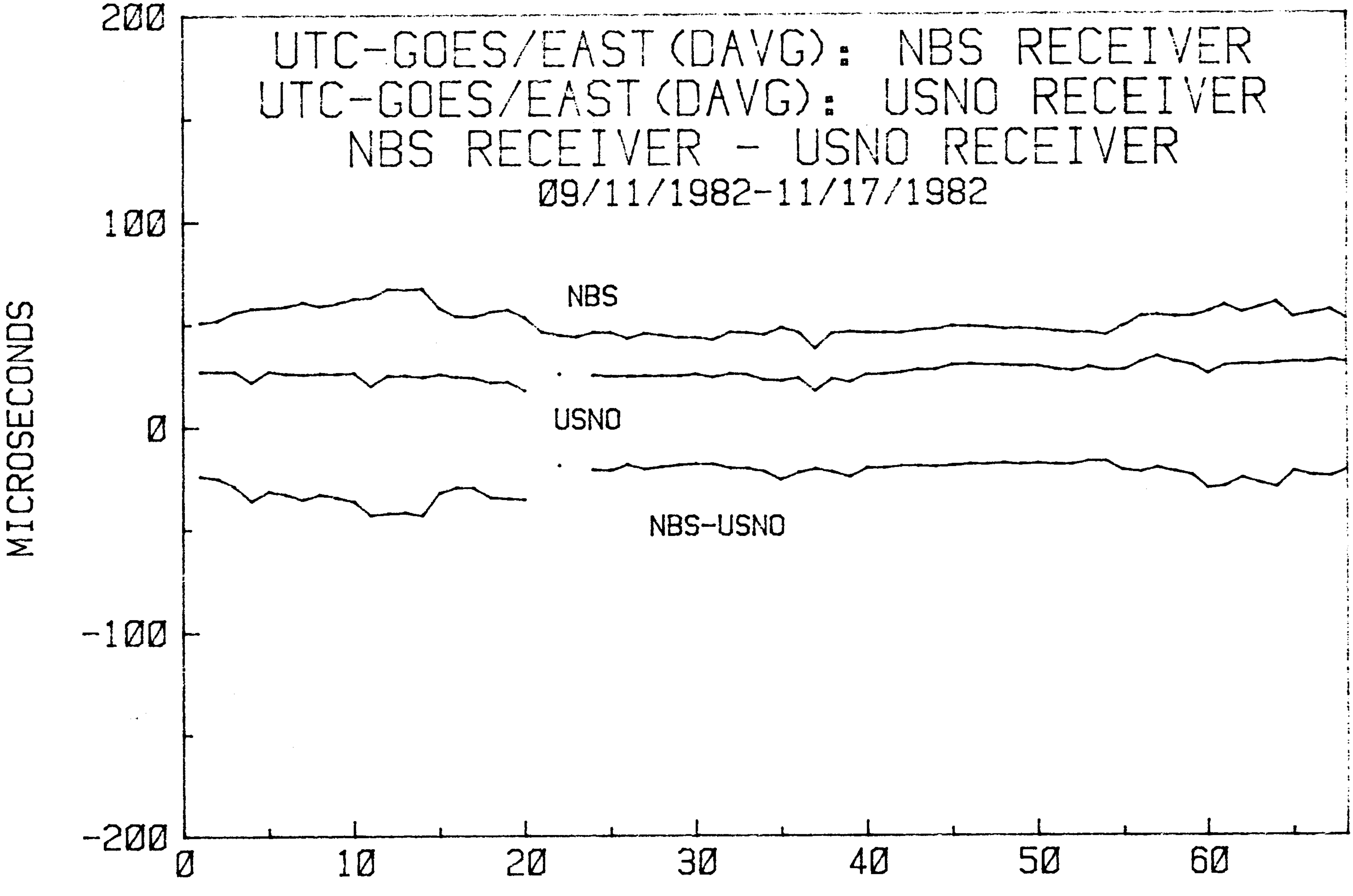
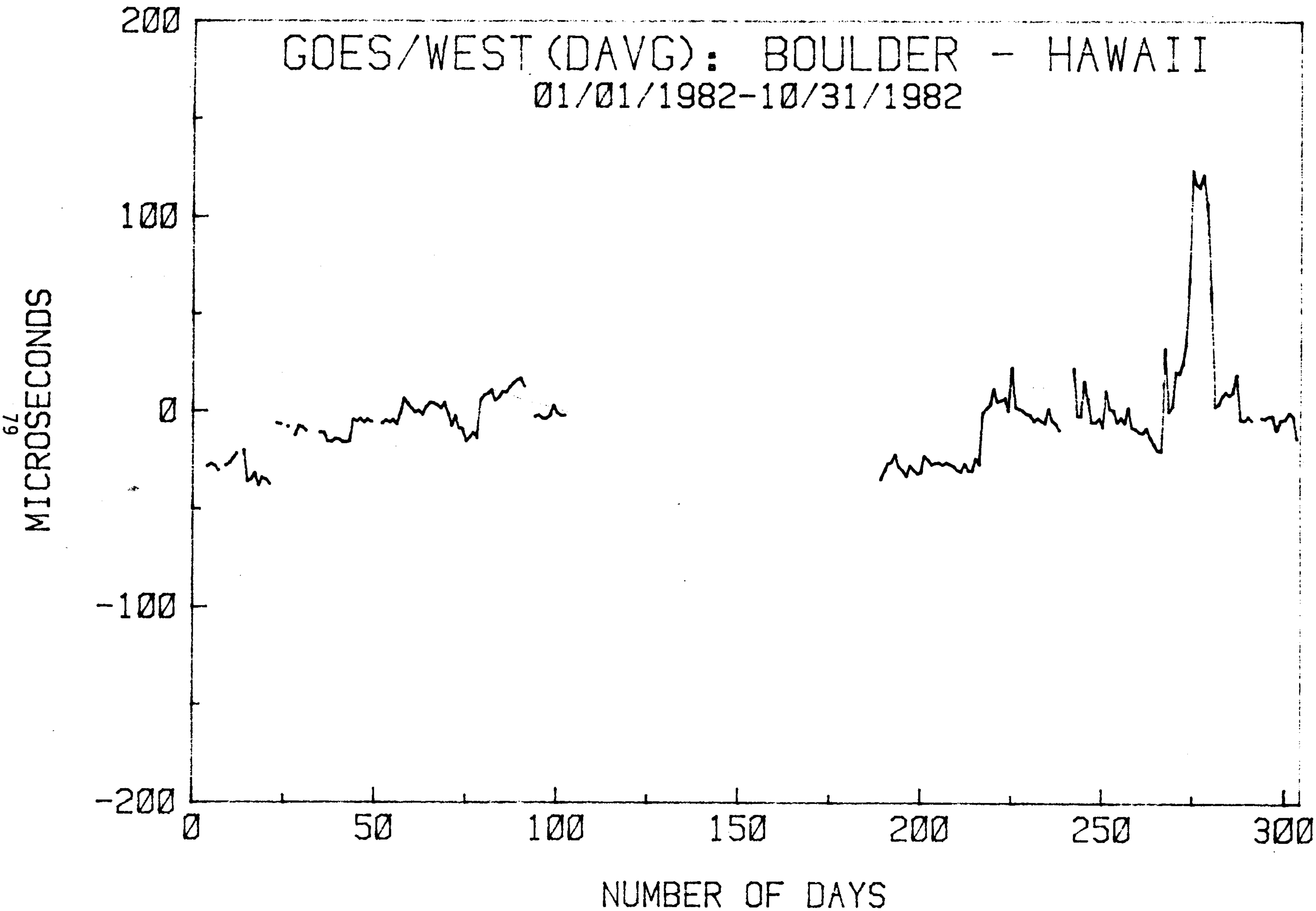

UTC-GOES/EAST(DAVG): NBS RECEIVER
UTC-GOES/EAST(DAVG): USNO RECEIVER
NBS RECEIVER - USNO RECEIVER
09/11/1982-11/17/1982
NBS
USNO
NBS-USNO
MICROSECONDS
200
100
0
-100
-200
0
10
20
30
40
50
60
NUMBER OF DAYS

Figure 13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01/01/1982-10/31/1982
200
100
0
-100
-200
MICROSECONDS
0
50
100
150
200
250
300
NUMBER OF DAYS

Figure 14